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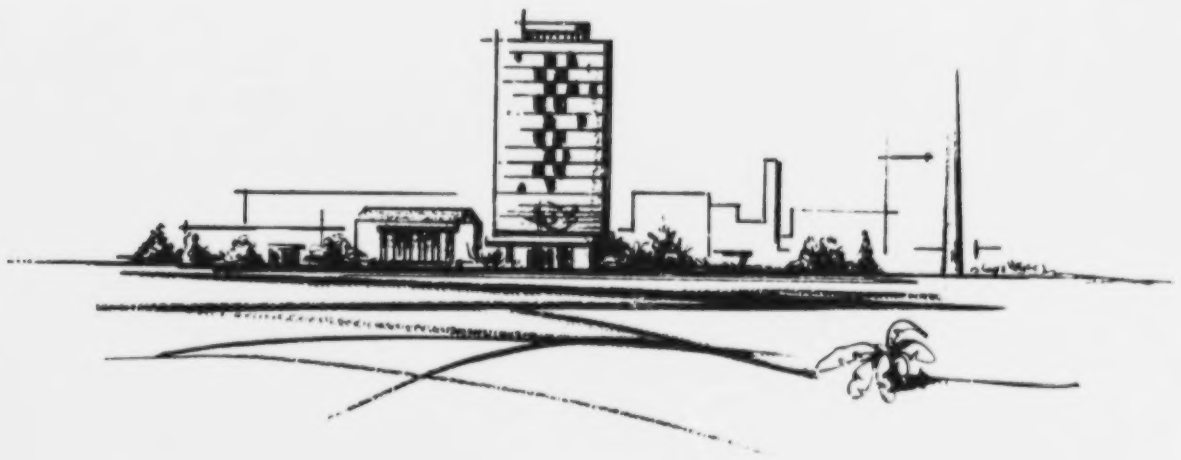

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SUMMARY REPORT

on

PREPARATION AND FIRING OF EMULSIONS OF NO. 2 FUEL OIL AND WATER

Contract No. 86-68-84
Task Order No. 8

to

NATIONAL AIR POLLUTION CONTROL ADMINISTRATION
Process Control Engineering Program

November 1, 1968

by

R. E. Barrett, J. W. Moody, and D. W. Locklin

BATTELLE MEMORIAL INSTITUTE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

ABSTRACT

This task report describes the development of techniques for the preparation of emulsions of No. 2 fuel oil and water. The resulting emulsions are suitable for firing in the experimental rig being used by NAPCA to investigate factors influencing emissions from domestic oil-heating equipment.

The wide range of available emulsifying agents was screened to a workable number by using the HLB concept. A blend of two commercially available emulsifying agents was identified as satisfactory for preparing water-in-oil emulsions that contained up to 53 percent water and were stable over a 10-week period.

Atomization of the emulsions by a high-pressure nozzle produced sprays having droplet size distributions similar to those for No. 2 fuel oil. Emulsions containing 5, 10, 19, 29, and 53 percent water were fired successfully in a conventional gun-type burner without modification.

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November 1, 1968

National Air Pollution Control Administration
3914 Virginia Avenue
Cincinnati, Ohio 45226

Attention Mr. John H. Wasser, Project Officer
Process Control Engineering Program

Gentlemen:

Contract PH 86-68-84
Task Order No. 8

We have completed our assignment under the subject task order and hereby enclose our summary report "Preparation and Firing of Emulsions of No. 2 Fuel Oil and Water".

The report outlines the procedure developed for preparation of fuel oil-water emulsions containing up to 50 percent water. Combustion trials confirmed that these emulsions can be successfully fired with the conventional gun-type oil burner now used in your NAPCA test rig.

If you have any questions, we would be pleased to discuss any of the points in greater detail.

Sincerely,

David W. Locklin
Associate Chief
Thermal Systems Division

DWL:jc

Enc. 20

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PREPARATION AND FIRING OF EMULSIONS OF NO. 2 FUEL OIL AND WATER

by

R. E. Barrett, J. W. Moody, and D. W. Locklin

The Process Control Engineering Program of the National Air Pollution Control Administration is presently evaluating methods of reducing air-pollutant emissions from combustion devices, including domestic oil burners for space heating. As a part of this program, NAPCA is conducting tests in a furnace which utilizes a 1-gph high-pressure atomizing burner firing commercial No. 2 fuel oil.[7,8] These tests will determine the extent to which air pollutants can be reduced by using various fuel additives in domestic-size oil-heating units.

NAPCA became interested in evaluating emulsified oil-water fuels as a result of reported improved combustion (evidenced by shorter combustion times) by others using these fuels. The concept of firing fuel oil-water emulsions to obtain secondary atomization and, therefore, improve combustion was advanced by Ivanov, and others[9], in 1957, and further discussed by Ivanov and Nefedov[10] in a 1962 paper. In the desired type of oil-water emulsion, each fuel oil droplet contains one or more small droplets of water. As the emulsion is sprayed into the combustion chamber, the water within the fuel droplet vaporizes before the fuel is consumed. The pressure generated within the fuel droplet by the vaporizing water is sufficient to rupture the fuel droplet in a miniature explosion. This shattering or secondary atomization of the fuel droplet causes further reduction in the fuel droplet size and exposes a greater surface area of fuel for vaporization, mixing, and burning, thus providing more rapid and improved combustion.

TASK OBJECTIVE

Battelle's assignment under this task order was to develop techniques for preparing emulsions containing up to 50 percent water in distillate fuel oil, and to develop a technique for firing the emulsions in the NAPCA experimental rig.

SUMMARY AND CONCLUSIONS

The objective of this task was accomplished. Relatively stable emulsions containing 5 to 53 percent water were produced in quantities of 1/2 to 2 gallons from commercial No. 2 fuel oil, distilled water, and commercial emulsifying agents. Satisfactory firing of these emulsions was accomplished in a laboratory combustion chamber with a burner identical to the burner used in NAPCA tests.

Stable water-in-oil emulsions were prepared by using a blend of 4 parts sorbitan sesquioleate and 1 part polyoxyethylene (20) sorbitan monopalmitate. The emulsions were prepared by dissolving the surfactant in commercial No. 2 fuel oil. Deionized water was added in one step and the mixture was stirred for two minutes in a Waring blender. At higher water contents, the procedures produced oil-in-water emulsions.

It should be pointed out that this task was not intended to produce the "optimum" oil-water emulsion. It is likely that a more stable emulsion and better control of particle size could be achieved by modification of the surfactant blend and further development of the mixing procedures.

Droplet size measurements were made on sprays of water-in-oil emulsions containing up to 53 percent water by weight. The amount of water added had little effect on droplet size.

Emulsions containing up to 53 percent water were fired in a furnace similar to the NAPCA furnace. Combustion appeared generally as good as when firing commercial fuel oil, although a perceptable change in the flame was observed when switching from firing emulsions on to firing fuel oil.

Combustion measurements were made on emulsions containing up to 29 percent water. The relationship of smoke and O_2 in the flue gas did not show any significant difference when firing fuel oil and emulsions at 1.0 gph. When firing at 1.25 gph, emulsified fuels required greater excess air to reduce smoke to acceptable values.

HISTORICAL BACKGROUND

The background in the literature will be discussed in two parts, pertaining (1) to the preparation of emulsified fuel, and (2) to their combustion.

Preparation of Emulsified Fuels

The formulation of a stable emulsion is as much an art as it is a science. Each system presents its own unique problem. The solution involves the selection of a surfactant and the proper means of mixing the components. Historically, the problem was solved empirically through trial and error. At present, however, there are available thousands of surfactants which can be used as emulsifying agents, and some means of simplifying the selection is required.

A review of the literature was of but little help in the present case. Recently, oil-in-water emulsions (o/w)[(a)] of JP-4 fuel and water have been developed to minimize the fire hazard associated with jet aircraft fuel[(13-15)]. However, there has been little published on emulsions of water as the internal phase in hydrocarbon fuels. The most pertinent references are the studies of Ford and Furmidge[(1)] on the stabilization

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(a) o/w: an emulsion of discrete oil droplets in a continuous phase of water

w/o: an emulsion of discrete water droplets in a continuous phase of oil

of water-in-oil emulsions using oil-soluble emulsifiers. These authors conclude that such emulsifiers must be hydrophobic[b] in character and must possess the correct hydrophilic[c]-lipophilic[d] balance (HLB) for the particular oil concerned.

The hydrophilic-lipophilic balance (HLB) is a concept introduced by Griffin[2] as a means of characterizing emulsifiers. The HLB expresses, numerically, the balance between the lipophilic and hydrophilic portion of a surfactant molecule. The HLB is a measure of the relative solubility of the surfactant in oil and water.

The HLB concept was developed into a systematic scheme for emulsifier selection by Atlas Chemical Industries, Inc.[3] The scheme involves, first, finding the required HLB for the desired emulsion then, second, screening only those surfactants having the required HLB. This is the technique used in this study to select an emulsifier to produce stable w/o distillate fuel oil-water emulsions.

Burning of Emulsified Fuels

The literature search relative to producing and burning emulsions consisted of:

1. Discussions with Battelle staff members having experience relating to the subject.
2. A survey of FACTS ("Fuel Abstracts and Current Titles") for the years 1955 to 1968.
3. A machine search of Defense Department AD reports by the Defense Documentation Center.
4. A machine search of NASA literature.

(b) hydrophobic: tendency not to be soluble in water

(c) hydrophilic: high tendency to be soluble in water

(d) lipophilic: high tendency to be soluble in oil.

In addition, the Air Pollution Technical Information Center was contacted, but no specific references were identified by the Center.

The machine literature searches revealed few references considered pertinent. In fact, most references uncovered in the search of Defense Department literature pertained to separation of water from fuel. A search of recent issues of FACTS also produced references primarily related to removing water from oil.

Discussions with Battelle staff members resulted in the identification of a number of references relating to producing and burning o/w emulsified fuels. These emulsions are intended as safer fuels for aircraft, especially helicopters. Although this literature was not especially pertinent or helpful for the present study, some of the material relating to corrosion problems may be useful if emulsified fuels become widely used. Therefore, references are given in the bibliography for some of these reports and papers[13-28].

Three papers appeared to be especially pertinent to the subject of burning water in oil emulsions:

1. The primary interest of the paper by Ivanov, et al.,[9] is preparation and burning of heavy or residual oils. They prepared w/o emulsions from several heavy oils and tars. Water droplet size was 2 to 8 microns. Experimental results include a description of the process occurring when a droplet of fuel or emulsion was injected into stationary air within a heated, closed-end tube. When a droplet of kerosine was injected into the heated air at 1300 F, there appeared to be evaporation of the liquid fuel followed by ignition and combustion of the vapors. However, when a droplet of water-in-oil emulsion (3 percent water in kerosine) was injected into heated air at 1150 F, the drop appeared to boil and break into fine particles before vaporizing and burning. Experiments with residual oil-water and tar-water emulsions produced similar results.

2. The paper by Ivanov and Nefedov[10] discusses combustion of individual 800 to 3000 micron drops of water-in-kerosine and water-in residual oil emulsions containing 20-40 percent water. Diameters of the water droplets were 10-50 microns. The authors reported boiling of the emulsion droplet followed by a "microexplosion" of the drop due to pressure from the boiling water. This microexplosion, or secondary atomization, appeared to reduce combustion times for the fuel droplets by 20 to 40 percent. The authors also reported that the emulsified fuels appeared to exhibit the same combustion improvements in practical furnaces as in the laboratory.

3. A paper, by Ludera[11], deals primarily with the viscosity reduction of water-in-oil emulsions when compared to the straight fuels. Reduction in viscosity appeared significant.

EXPERIMENTAL PROCEDURES AND RESULTS

The experimental portion of this study consisted of two parts: (1) determining procedures for making emulsified fuels and making sufficient quantities for combustion trials, and (2) firing the emulsions in a combustion chamber similar to that employed by NAPCA.

Although the scope of the task order for this project included both distillate and residual fuels, experimental trials were limited to distillate fuel emulsions.

Preparation of Emulsified Fuels

Determination of Required HLB

A kit* of surfactants of known HLB values ranging from 2 to 20 was used to determine the required HLB for the w/o emulsion desired.

---

* Atlas Chemical Industries, Inc.

One cc of the surfactant was dissolved in 200 cc of No. 2 fuel oil. Ten cc of deionized water was added in one step. The materials were then stirred for one minute on the Waring blender. The emulsions were then poured into 8 oz. narrow-mouth bottles and were allowed to stand.

Table 1 is a summary of the results obtained. The most stable emulsions were obtained with surfactants of HLB values of 4 and 6. In this series of tests the surfactants were used in concentrations of less than 1 weight percent.

TABLE 1. DETERMINATION OF REQUIRED HLB

Test Number	HLB Value	Results and Observations
1	2	Emulsion milky and opaque-immediate separation
2	4	Emulsion milky and opaque-separation within 1/2 hour
3	6	Emulsion milky and opaque-partial separation within 1 hour
4	8	Emulsion milky and opaque-immediate separation
5	10	Emulsion milky and opaque-immediate separation

Table 2 summarizes the results of another series of tests using increased amounts of the surfactants. As before, the surfactants were dissolved in 200 cc of No. 2 fuel oil; 10 cc of deionized water was added and the mixture was stirred for one minute in the Waring blender. Again, the most stable emulsions were obtained with a surfactant of HLB 6.

The results indicate that, for the particular surfactants and fuel oil used, the optimum surfactant concentration was 2-3 weight percent. For other surfactants and fuel oils, the optimum concentration would probably vary.

The HLB value and surfactant concentrations determined in these tests are consistent with the behavior reported for other w/o emulsions[4,5].

TABLE 2. EFFECT OF SURFACTANT CONCENTRATION ON STABILITY OF EMULSION

Test Number	HLB Value	Volume of Surfactant (cc)	Results and Observations
1A	2	5	Emulsion separates immediately
2A	4	5	Emulsion separates overnight
3A	6	5	Stable emulsion but tends to separate in time
3C	6	3	Stable emulsion - tends to cream in time - does not break
4C	8	3	Emulsion separates immediately

Screening of Emulsifiers

Having determined the required HLB, a number of commercially available surfactants were screened. Those surfactants having HLB values of about 4-6 were selected for these tests. However, in many cases the HLB value of the candidate surfactants were not known. To calculate or measure the HLB value of these surfactants was beyond the scope of this program. Therefore, when the HLB value of a surfactant was not readily available, McCuteheon's[6] description of the surfactant and its uses served as a basis for inclusion in the screening test. The HLB factor of a surfactant blend is equal to the weighted average HLB of the ingredients. Therefore, any desired HLB may be obtained by blending compatible surfactants in the proper ratio.

Because the emulsions were to be used as fuel, prime consideration was given to those surfactants which would yield no residue or undesirable product when burnt. Thus, surfactants such as the metallic soaps and sulfur-containing compounds were not used in these tests.

The emulsions were prepared by dissolving the candidate surfactant in No. 2 fuel oil. Deionized water was added in one step and the mixture was stirred for 2 minutes on the Waring blender. About 200 cc of emulsion was prepared. The emulsions were stored in 8 oz narrow-mouth bottles.

Table 3 is a summary of the surfactants tested and the results obtained. The emulsions rated moderately stable tended to break or separate after several days standing. The stable emulsions did not break during a 10-week period. However, these emulsions did tend to "cream"; that is, the dense phase tended to settle to the bottom of the container. These emulsions could be re-homogenized readily by shaking.

Moderately stable emulsions were obtained by use of sorbitan sesquioleate (Arlacel C) and a modified phthalic glycerol alkyd resin (Triton B-1956).

TABLE 3. SCREENING OF COMMERCIAL SURFACTANTS

Formula Number	Surfactant Trade Name	Surfactant Chemical Name	HLB Value	Manufacturer	Emulsion Formula Concentration, Weight Percent No.2 Oil	Water	Surfactant	Results
6	Span 60	Sorbitan monostearate	4.7	(1)	93.2	5.6	1.2	Breaks immediately
7	Arlacel C	Sorbitan sesquioleate	3.5	(1)	93.2	5.6	1.2	Moderately stable
7A	Arlacel C	Sorbitan sesquioleate	3.5	(1)	92.3	5.5	2.2	Moderately stable
8	Triton B-1956	Modified phthalic glycerol alkyl resin		(2)	93.2	5.6	1.2	Moderately stable
8A	Triton B-1956	Modified phthalic glycerol alkyl resin		(2)	91.8	5.5	2.7	Moderately stable
9	Dispersant NI-0	Condensation product of ethylene oxide and an alkyl phenol		(3)	93.2	5.6	1.2	Breaks immediately
9A	Dispersant NI-0	Condensation product of ethylene oxide and an alkyl phenol		(3)	91.8	5.5	2.7	Breaks immediately
10	Igepal CO-530	Nonylphenoxypoly (ethyleneoxy) ethanol		(4)	93.2	5.6	1.2	Breaks immediately
11	Mulsor No. 8	Long chain fatty acid ester of glycols		(5)	93.2	5.6	1.2	Breaks immediately
12	Igepal CO-430	Nonylphenoxypoly (ethyleneoxy) ethanol		(4)	93.2	5.5	1.2	Breaks immediately
13*	4 Arlacel C 1 Tween 40	Sorbitan sesquioleate Polyoxyethylene (20) sorbitan monopalmitate	3.5 15.7 6	(1)	93.2	5.5	1.2	Stable emulsion
13A*	4 Arlacel C 1 Tween 40	Sorbitan sesquioleate Polyoxyethylene (20) sorbitan monopalmitate	3.5 15.7 6	(1)	87.0	10.4	2.6	Stable emulsion

* Note: The surfactants used in Formulas 13 and 13A consisted of a blend of 4 parts (by weight) Arlacel C and 1 part Tween 40. The HLB of the blend was 6.

List of Manufacturers
(1) Atlas Chemical Industries, Inc.
(2) Rohm and Haas Co.
(3) Oronite Division, California Chemical Co.
(4) General Aniline and Film Corp.
(5) Synthetic Chemicals, Inc.

The most stable emulsions were obtained by use of a blend of sorbitan sesquioleate and polyoxyethylene (20) sorbitan monopalmitate (Tween 40). In this case, 4 parts of sorbitan sesquioleate (HLB 3.5 molecular weight 560) was blended with 1 part polyoxyethylene (20) sorbitan monopalmitate (HLB 15.7 molecular weight 1290) to give a surfactant blend of HLB about 6 -- the required HLB of the desired emulsion. The molecular weight of the blend can be taken as 706 for the purposes of calculation.

Three qualitative tests were used to determine the type of emulsion (w/o or o/w) obtained.

First, the emulsions were examined under an ultra-violet lamp. If oil was the continuous phase, the emulsion would fluoresce uniformly. If water were the continuous phase, the fluorescence would be spotty.

Second, a small amount of a solid, oil-soluble dye was added to a few cc of the emulsion. If oil were the continuous phase, the dye would dissolve and the emulsion would be colored. These tests were checked by adding a water-soluble dye to a second portion of the emulsion. If oil were the continuous phase,the dye would not dissolve; however, if water were the continuous phase, the dye would dissolve and the emulsion would be colored.

Finally, the type emulsion was tested by carefully floating a drop of oil or water on a few cc of the emulsion. If oil were the continuous phase, the oil drop would disperse but not the water drop. If water were the continuous phase, only the water drop would disperse.

In every case these tests proved both the moderately stable and stable emulsions included in Table 3 were water-in-oil (w/o) emulsions.

Attempts were made to measure the droplet size of the internal phase of the stable emulsions by optical microscopy. However, because of rapid Brownian movement and the coalescence of droplets when the emulsion was placed on the microscope slide, it was not possible to measure the droplet size accurately. From the observations it is estimated that the average water droplet size was about 1 micron in diameter.

Preparation of Stable w/o Emulsions for Combustion Trials

A series of stable emulsions containing various amounts of water was prepared for the combustion trials by using the surfactant blend described in the previous section (4 parts Arlacel C to 1 part Tween 40). As before, the emulsions were prepared by dissolving the surfactant in No. 2 fuel oil. Deionized water was added in one step and the mixture was stirred two minutes on the Waring blender. Samples for combustion trials (1/2 to 2 gallon) were prepared in batches of 200-250 cc.

Table 4 summarizes the formulas of the stable emulsions. Stable w/o emulsions containing up to 53 weight percent water in the internal phase were prepared using the surfactant blend. The emulsion containing about 68 weight percent water (Formula 13F) proved to be an o/w type emulsion. (Samples of this emulsion were not prepared for combustion or burner trials.) Thus, the distillate fuel oil-water emulsions prepared by these procedures invert at water concentrates between 53 and 68 weight percent.

TABLE 4. FORMULAS FOR STABLE EMULSIONS

Formula Number	Concentration, Weight Percent			Emulsion Type
	No. 2 Fuel Oil**	Water	Surfactant*	
13	93.2	5.5	1.2	w/o
13A	87.0	10.4	2.6	w/o
13B	78.9	18.8	2.3	w/o
13C	72.1	25.8	2.1	w/o
13D	69.0	28.8	2.2	w/o
13E	44.5	52.8	2.7	w/o
13F	28.7	67.9	3.4	o/w

* Note: Surfactant consisted of 4 parts (by weight) of sorbitan sesquioleate and 1 part polyoxyethylene (20) sorbitan monopalmitate--average molecular weight of 706.

** 36^{o} API Gravity @ 60 F.

Burning of Emulsified Fuels

Description of Burner

To test fire the emulsions and assure that satisfactory combustion was attainable, a burner and combustion chamber rig was constructed as similar as practical to the NAPCA rig. Details of the NAPCA rig were obtained from the description in the 1966 paper by Wasser, Hangebrauck, and Schwartz[7] and from discussions and observations during a visit to the NAPCA lab by project personnel.

Figure 1 shows the current version[8] of the experimental furnace used for the NAPCA trials. The combustion chamber of the NAPCA furnace shown is 12 inches higher than described in the 1966 paper[7].

Figure 2 shows the combustion chamber constructed at Battelle using K-30 firebrick lined with Fiberfrax. It is identical in configuration to the NAPCA furnace. The heat-exchanger section of the apparatus constructed at Battelle is somewhat simpler in design than that of the NAPCA furnace. For conditions where relatively good combustion is obtained, the design of the heat-exchanger section should not significantly affect the flame.

The gun burners used in both furnaces are identical. These burners were manufactured by the Automatic Burner Corporation and are designated as ABC Model 55J1 oil burners having No. 8269, 2-1/4-inch diameter chokes; No. 7397, 3-1/2-inch diameter solid B-type static-pressure disks; 7-3/4 inch long air tubes; and R-818481188 primary air cans. Delavan 1.00 and 1.25 GPH, 80-degree Type A pressure-atomizing nozzles were used at a pressure of 100 psi. While this burner is not the most recent ABC design available, it is essentially identical to the one operated by NAPCA.

Effect of the Emulsion on Atomization

One of the most significant factors affecting the combustion of any liquid fuel is the droplet size of the atomized fuel spray. Converting commercial fuel oil into a w/o emulsion could be expected to alter the fuel properties which affect droplet size, namely viscosity, density, and surface tension. Therefore, it was considered important to measure the droplet size of unburned sprays of the w/o emulsions. Examination of these sprays could also show if the emulsion was breaking up during the atomization process, a phenomena which occurs for many o/w emulsion fuels considered for aircraft application.

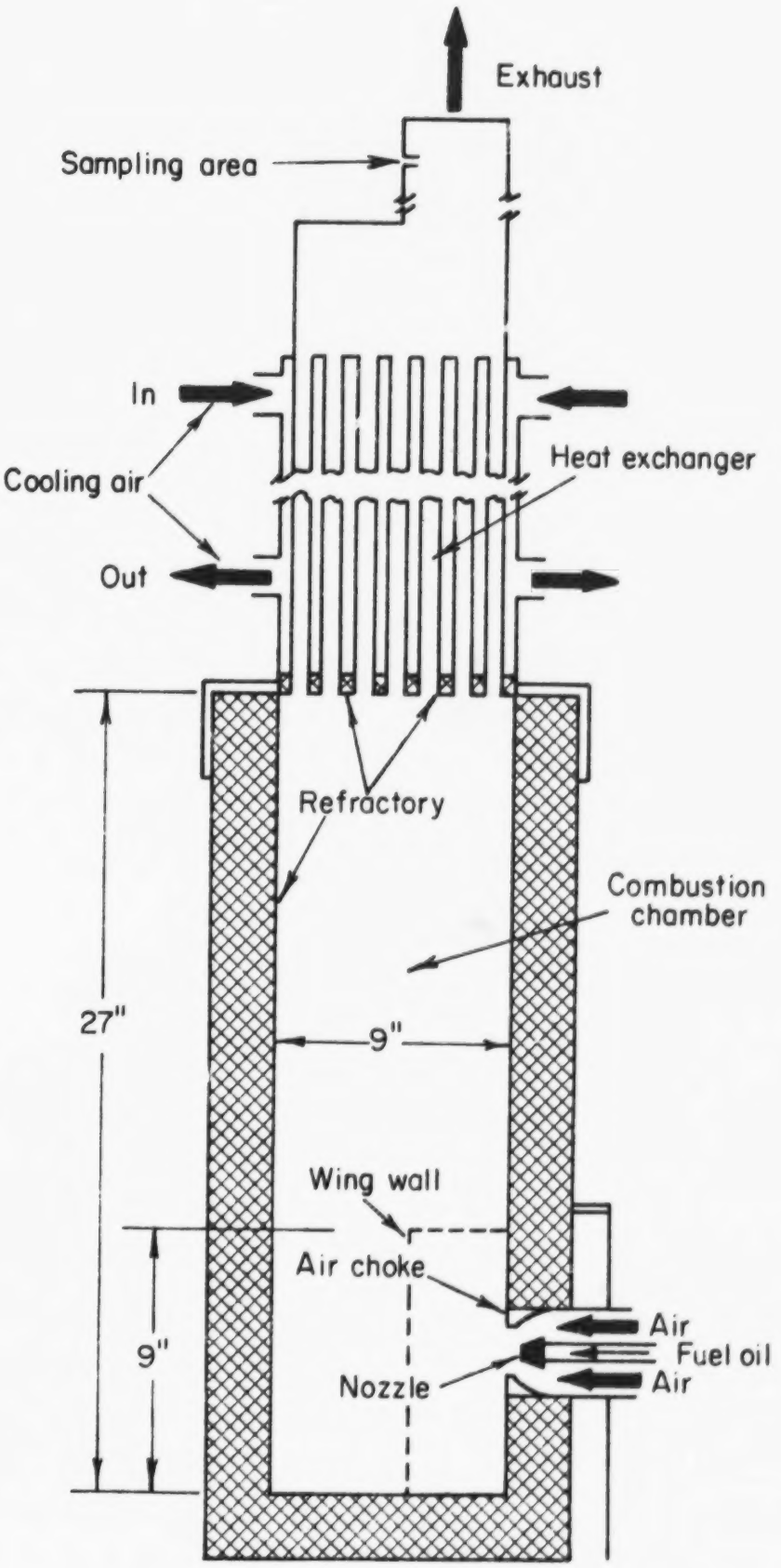

FIGURE 1. NAPCA EXPERIMENTAL FURNACE[8]

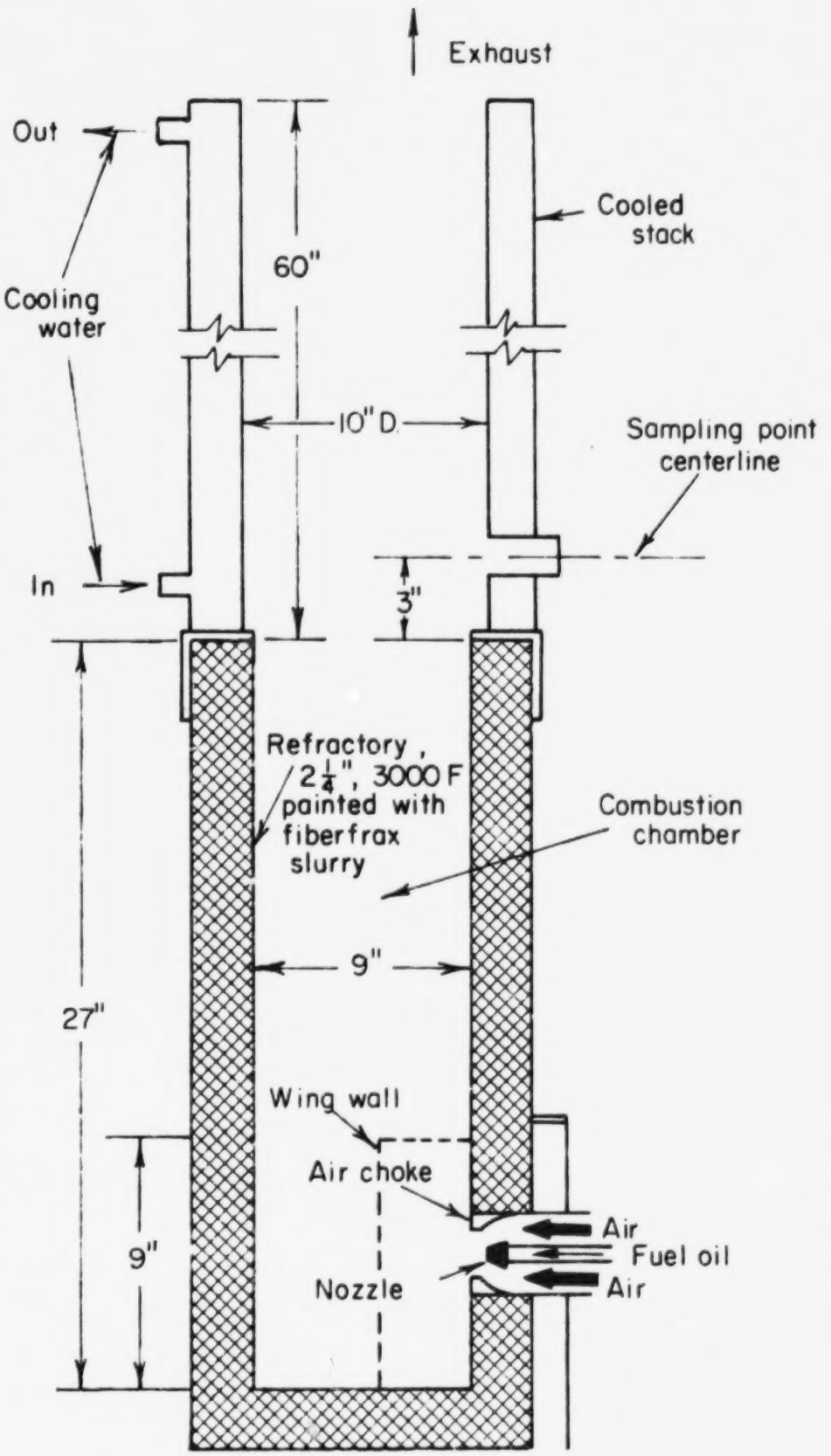

FIGURE 2. BATTELLE EXPERIMENTAL APPARATUS

Cold-spray atomization studies were made by pumping the fuel through the gun-burner nozzle and passing a magnesium-oxide-covered slide through the spray. The burner ignition and control circuits were disconnected for these experiments. The slides were examined under a microscope with a Filar micrometer eyepiece and the diameters of 200 craters were measured. Droplet diameter was determined from the slide craters by the following correlation[4]: (droplet diameter) = 0.82 x (crater diameter).

Figures 3 and 4 show the results of these droplet-size measurements for commercial No. 2 fuel oil and for oil-water emulsions containing 5, 10, 19, 29, and 53 percent water.

Table 5 lists number-mean diameters and calculated mass-mean diameters (using an assumed normal distribution of particle sizes) for each fuel. These droplet sizes are in general agreement with those reported by Tate and Olson[12]: 83 micron mass-mean diameter for 1-gph hollow cone nozzles of typical commercial design and atomizing No. 2 fuel oil.

TABLE 5. DROPLET SPRAY SIZES

Test Run	Fuel	Number mean diam., microns	Mass mean diam., microns
A-1	No. 2 fueloil	30	58
A-2	Emulsion - 5% water	32	60
A-3	Emulsion - 10% water	37.5	76
A-4	Emulsion - 19% water	34	70
B-1	No. 2 fueloil	31	77
B-2	Emulsion - 29% water	32	79
B-3	Emulsion - 53% water	33	81

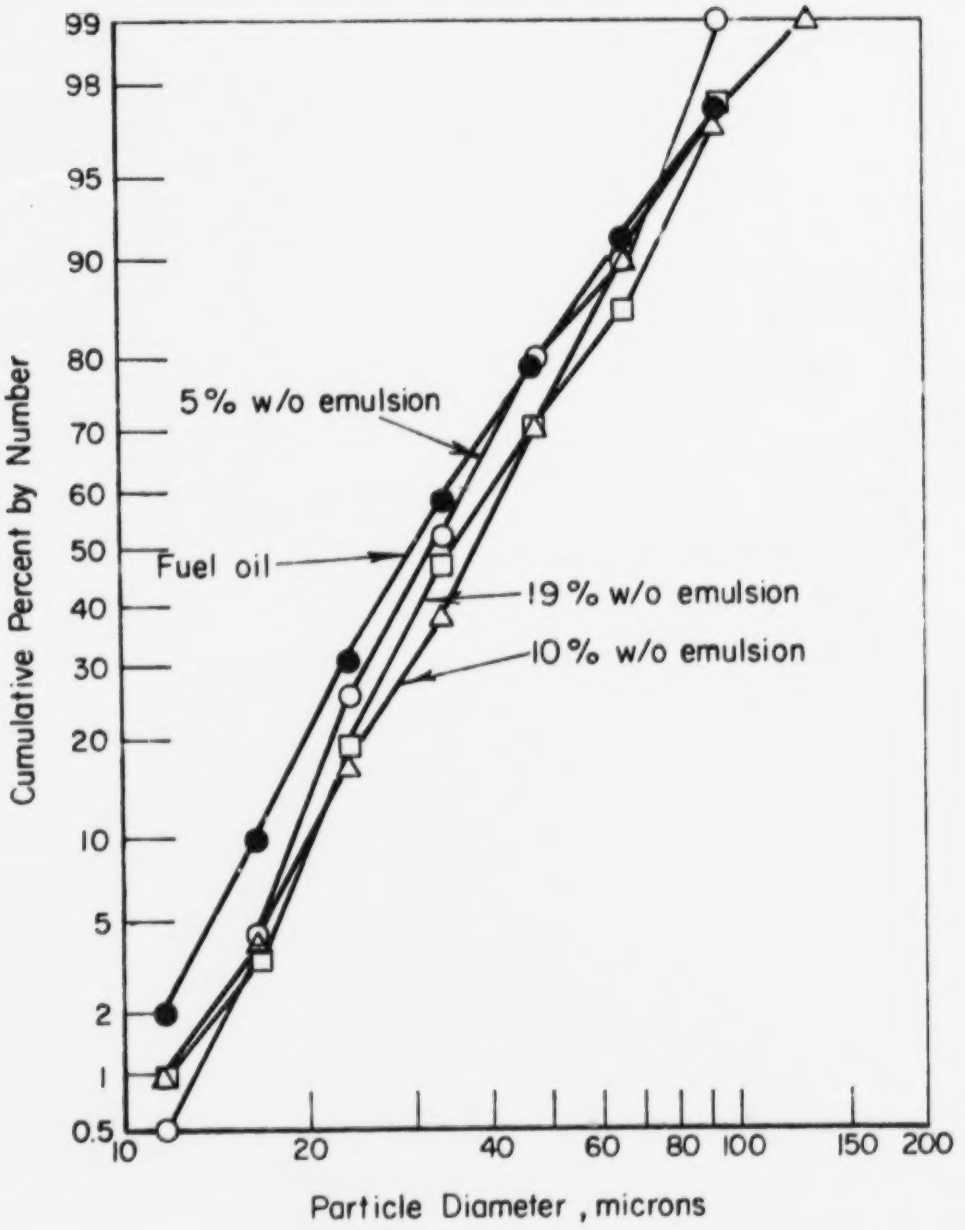

FIGURE 3. DROPLET SIZE DISTRIBUTIONS FOR FUEL OIL AND EMULSIONS CONTAINING 5, 10, AND 19 PERCENT WATER-TEST, SERIES A

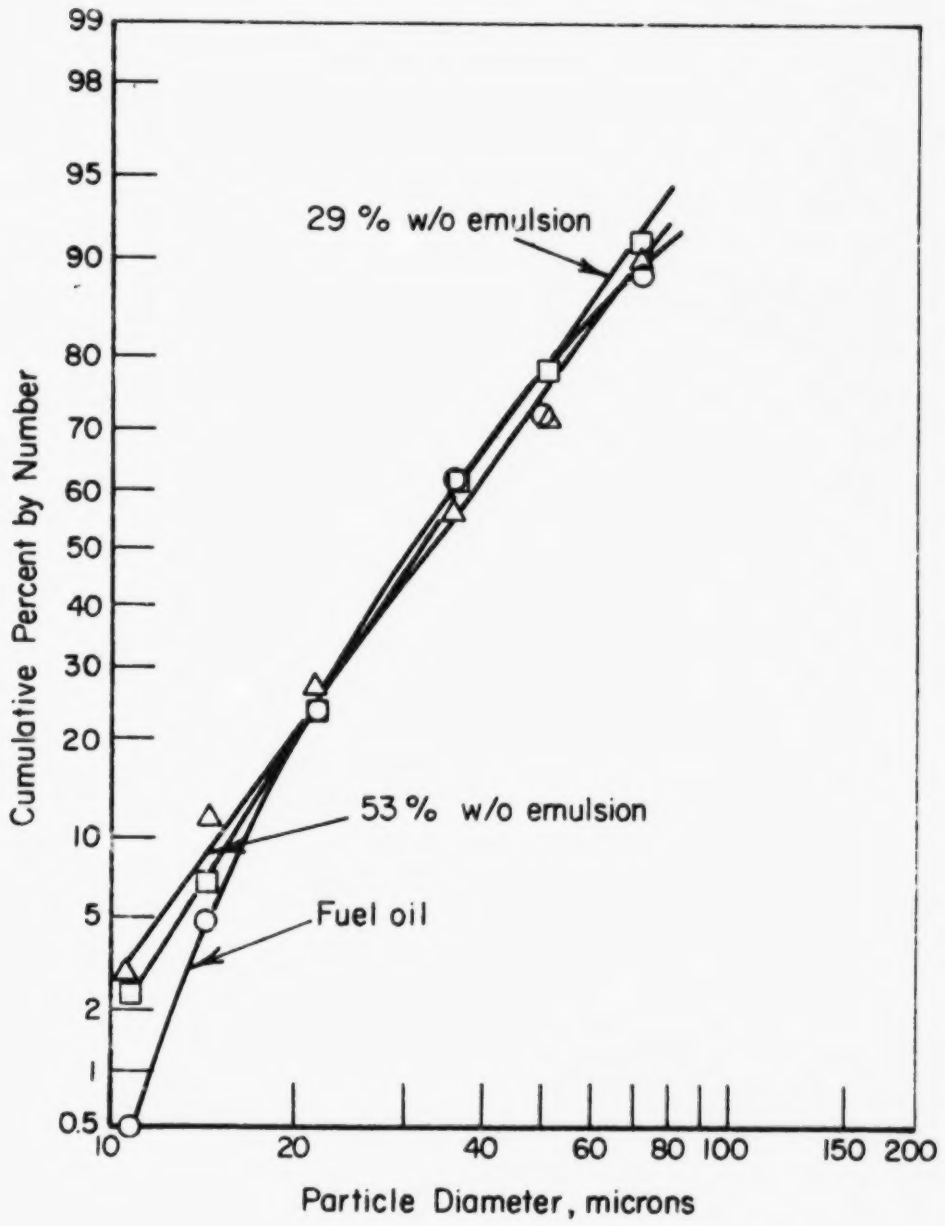

FIGURE 4. DROPLET SIZE DISTRIBUTIONS FOR FUEL OIL AND EMULSIONS CONTAINING 29 AND 53 PERCENT WATER, TEST SERIES B

Examination of droplets collected on glass slides while spraying a 10 percent water emulsion showed that the emulsion did not break up during the spraying process and that each droplet of oil contained droplets of water estimated to be about 2 microns in diameter.

Combustion Trials

Each emulsion was fired in the combustion chamber to determine general combustion characteristics of these fuels. Observations were of two types: (1) qualitative observations of the flames were made to determine if combustion appeared to be satisfactory on a gross scale (for emulsions up to 53 percent water); (2) quantitative measurements were made of oxygen, combustibles, and smoke in the flue gas (for emulsions up to 29 percent water).

O_2 and percent combustibles in the flue gas were measured with a Bailey Heat Prover and smoke measurements were made with the motorized Bacharach smoke meter Model No. RDC (see Figure 2 for location). Measurements for all data points indicated that combustibles were below 1000 ppm, the threshold of sensitivity for the Heat Prover.

Each oil-water emulsion appeared to burn with about the same flame volume and color as No. 2 fuel oil. Although there was a perceptible change in flame appearance when switching from commercial fuel oil to emulsions and back to fuel oil, no gross change in flame volume or length or flame characteristic was observed.

Table 6 and Figures 5, 6, and 7 summarize the combustion data. Considerable scatter of data is noted. Individual points within a given trial were fairly consistent; however, reproducibility between apparently similar trials was lacking.

TABLE 6. RESULTS OF COMBUSTION TESTS FOR COMMERCIAL NO. 2 FUEL OIL AND w/o EMULSIONS

Test	Water in fuel, volume percent	Water in fuel, weight percent	Nozzle capacity, gph	Nozzle pressure, psi	Oxygen in flue gas at No. 2 smoke, percent	Fuel temperature, F	Firing rate, Btu/hr
1	0	0	1.00	100	2.3	76-86	127,000
2	5	6	1.00	100	2.1	-	-
3	9	10	1.00	100	2.1	82-96	99,000
4	17	19	1.00	100	2.9	86-97	84,000
5	0	0	1.00	100	3.8	77-89	112,000
6	0	0	1.00	100	3.0	76-85	110,000
7	0	0	1.25	100	0.9	83-92	129,000
8	17	19	1.25	103	2.5	81-91	110,000
9	0	0	1.25	102	0.9	74-87	130,000
10	26	29	1.25	102	3.4	78-88	103,000
11	0	0	1.00	100	2.4	76-82	114,000
12	0	0	1.00	100	3.0	74-84	109,000
13	17	19	1.00	100	2.4	79-89	95,000

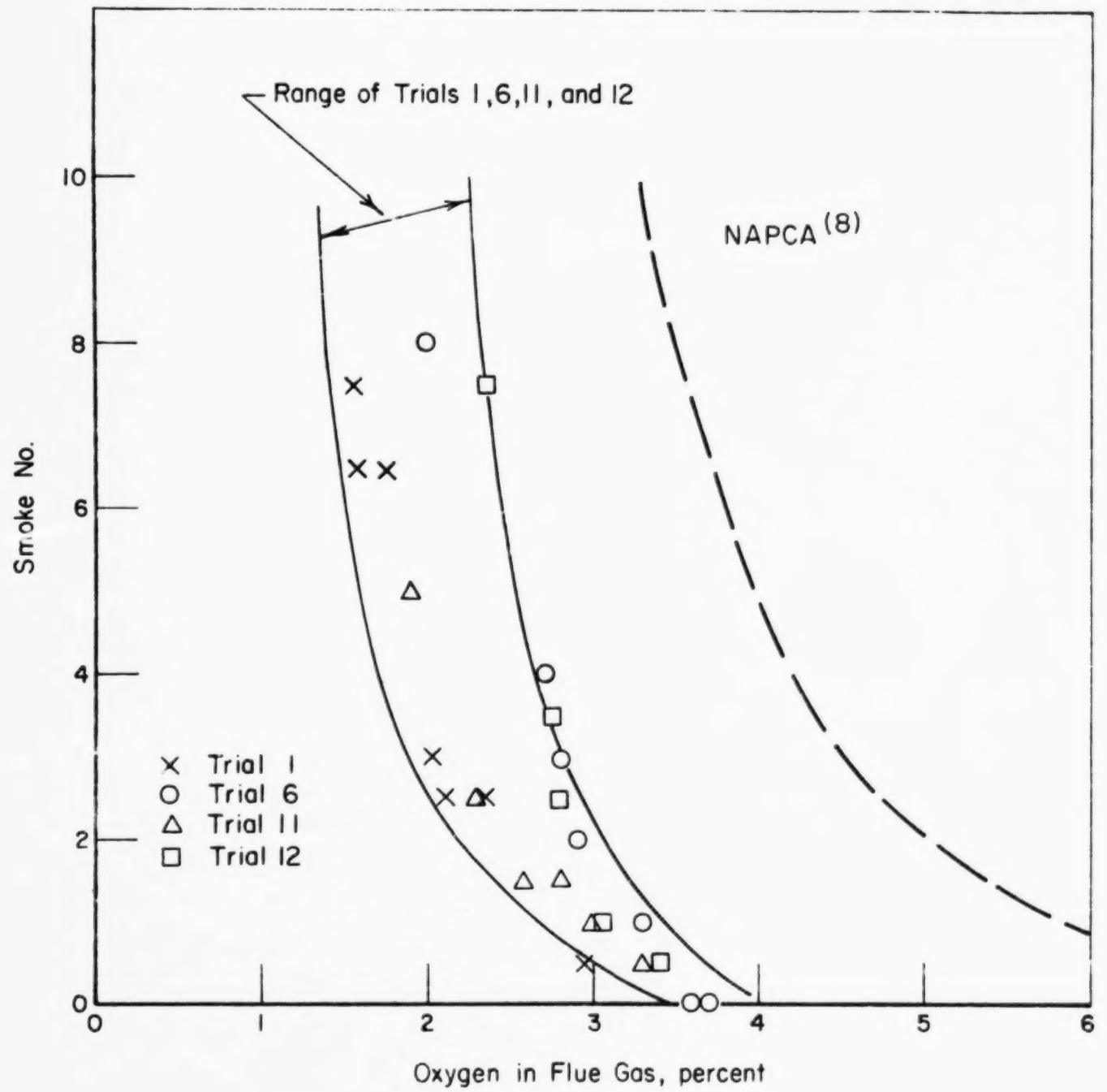

FIGURE 5. SMOKE FROM BURNING COMMERCIAL NO. 2 FUEL OIL AT 1.00 GPH

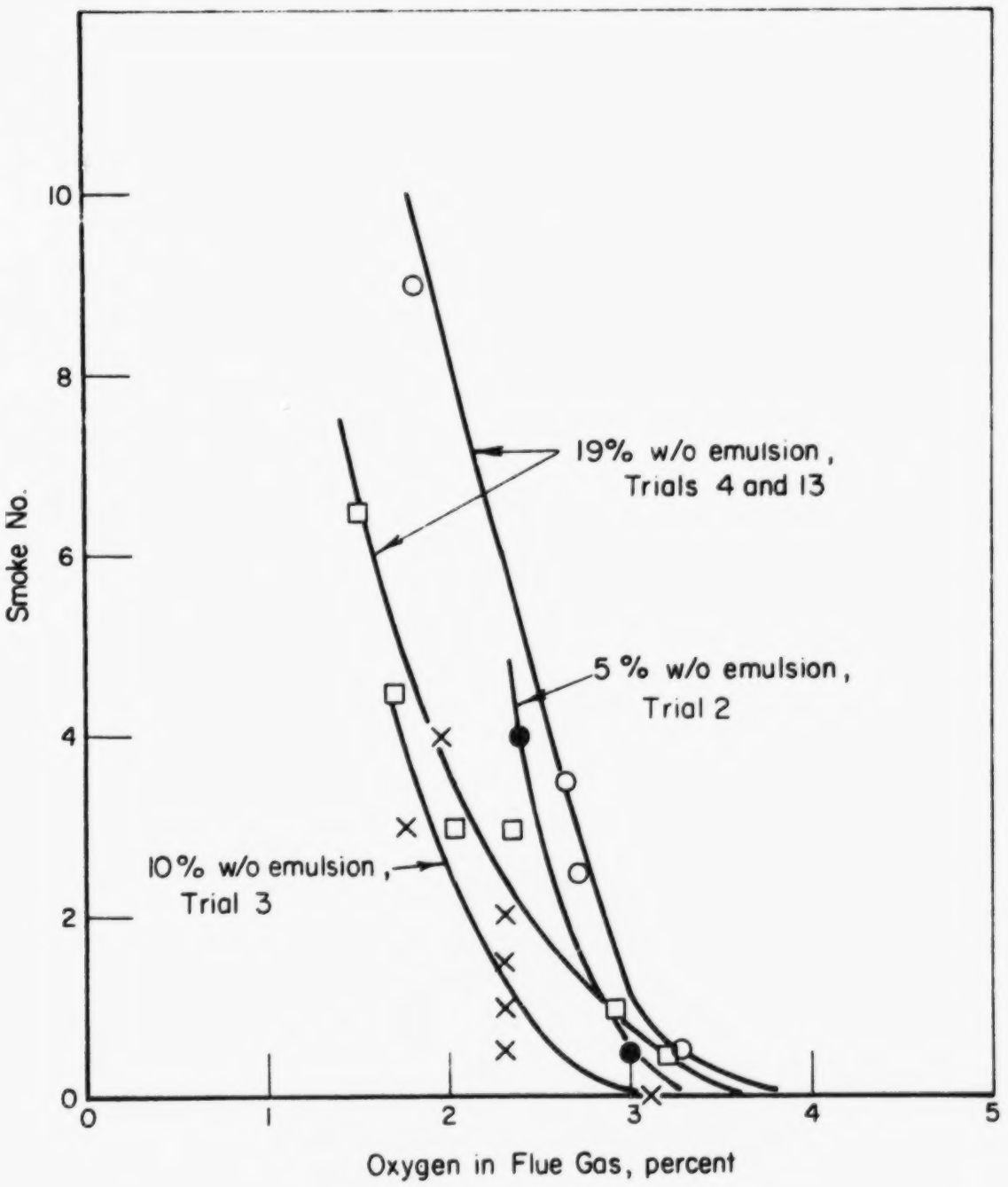

FIGURE 6. SMOKE FROM BURNING FUEL OIL EMULSIONS AT 1.00 GPH

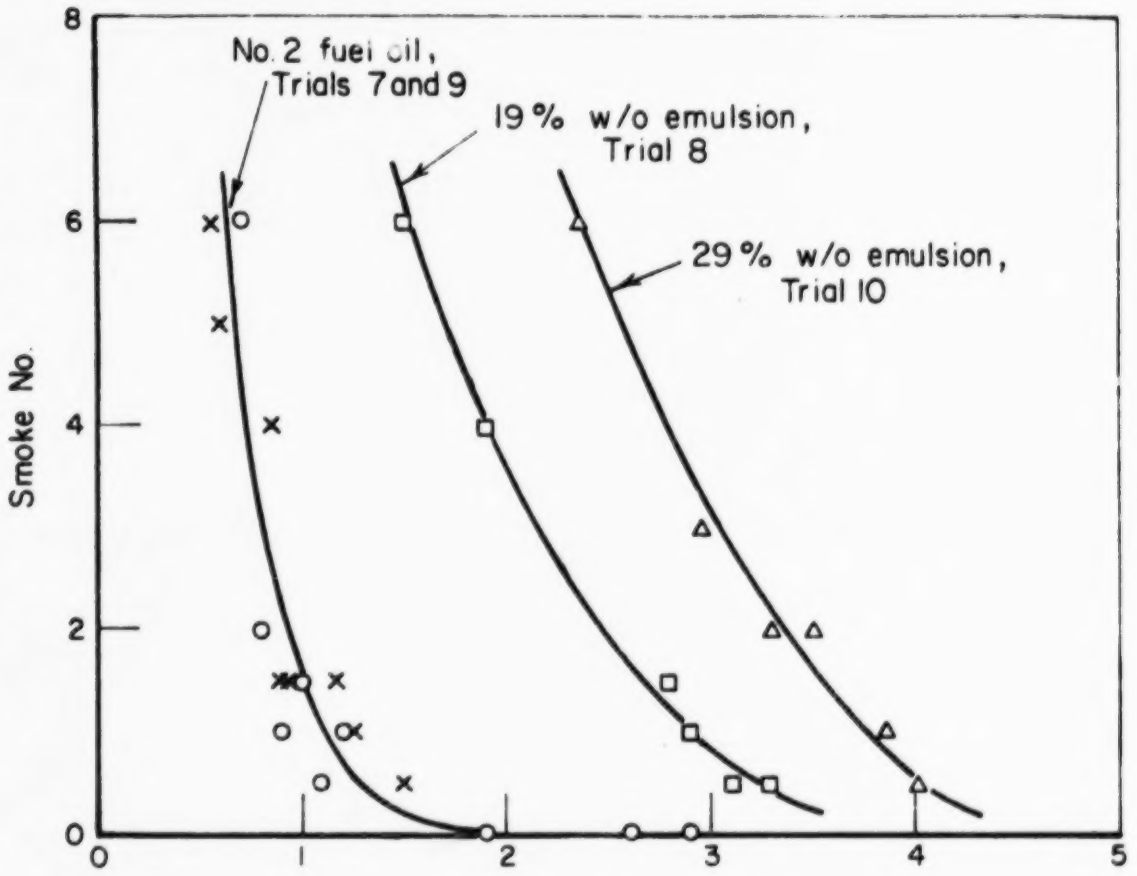

FIGURE 7. SMOKE FROM BURNING NO. 2 FUEL OIL AND TWO W/O EMULSIONS AT 1.25 GPH

For the 1-gph nozzle (Figures 5 and 6), the addition of water up to 29 percent did not have a consistent effect on the smoke vs O_2 relationship, within the reproducibility of the data. For the 1.25 gph nozzle, higher percentages of water required consistently higher excess air for the same smoke level.

The performance characteristic reported for the NAPCA test rig[8], also shown in Figure 5, suggests a significant difference in combustion conditions for that rig. Residence time and air patterns in the two rigs should be similar by design, so it is possible that the different characteristic is due to differences in atomization, fuel characteristics, or combustion-zone temperature.

COMMENTS

The incentive for investigating the firing of emulsified fuels lies in the potential benefits of reducing emissions of gaseous pollutants. It was recognized at the outset that the emulsified No. 2 oil might not show any substantial improvement in smoke performance. Because commercial No. 2 fuel oil readily atomizes into fine droplets, secondary atomization is not essential to clean combustion when firing this fuel with a proper burner. The concept may be more effective in reducing both smoke and gaseous emissions when applied to residual fuels, where atomization and burning is more difficult.

Practical Considerations in Utilizing Emulsified Fuels

A few of the practical considerations of using fuel oil-water emulsions are discussed below.

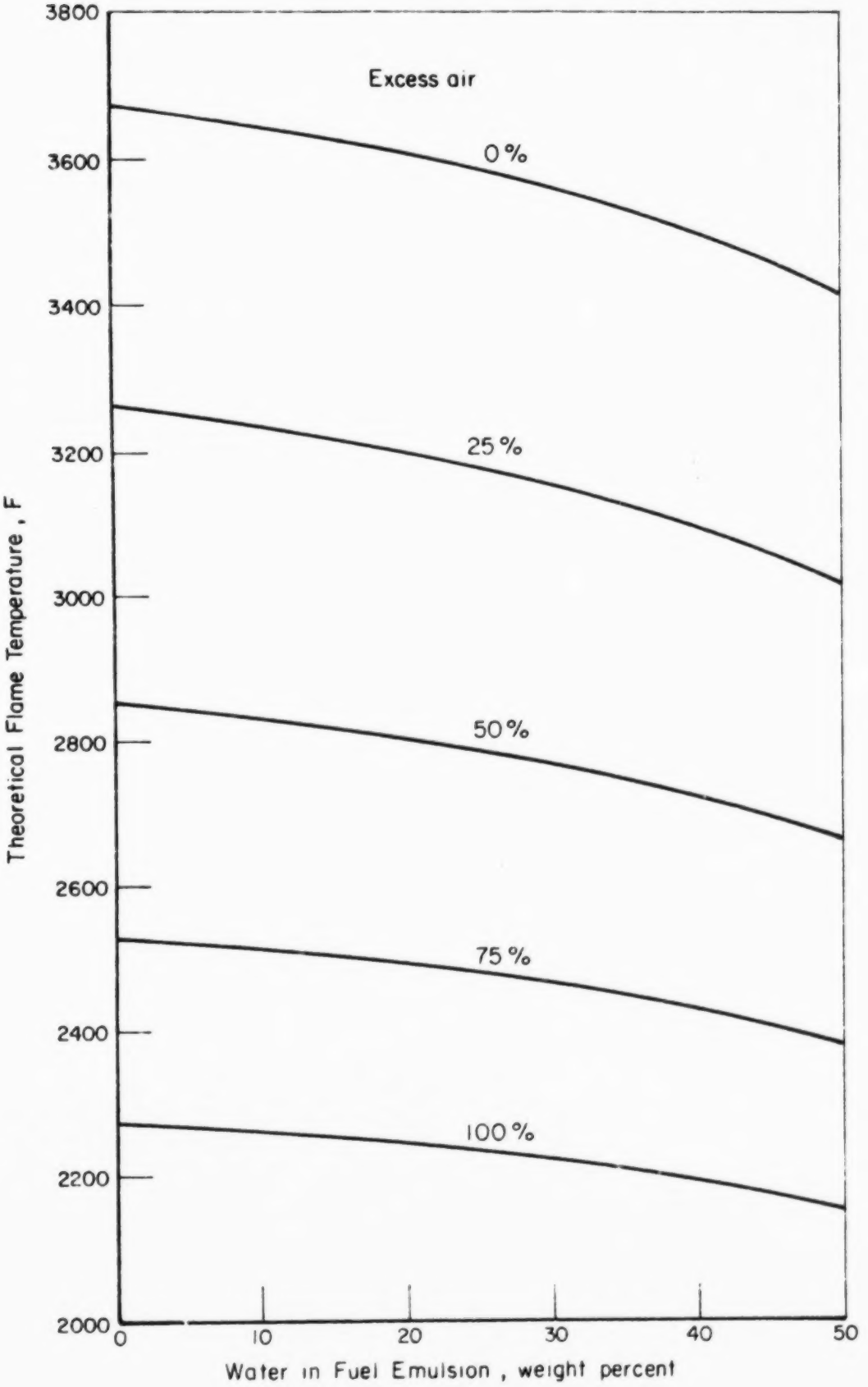

FIGURE 8. THEORETICAL FLAME TEMPERATURES

Logistics

Several logistic schemes might be considered for producing emulsified fuels for commercial use.

Fuel emulsions could be generated at the refinery as a final step in producing the marketable fuel. The fuel would then be distributed, stored, and fired as an emulsion. This would require stable emulsions and would result in an increased transportation cost per Btu delivered, as the water in the emulsion would be shipped with the fuel.

A reduction in the long-distance transportation cost could be achieved by preparing the emulsions just prior to local delivery of the fuel. This would require each fuel distributor be equipped for producing emulsions.

Another method of preparing emulsions would be to generate the emulsion at the point of consumption, just prior to firing the fuel. If the emulsifying agent were already in the fuel as an additive, only water would need to be added at the furnace. This might require a special mixing device, or the fuel pump might be used for the mixing. It is possible that the emulsion might even be produced at the nozzle. Generating emulsions at the burner was not attempted in this study as the object was not to develop a practical commercial scheme but, rather, to accomplish firing of emulsified fuels for experimental purposes.

Potential Problems

Several problems may be encountered if emulsified fuels are introduced as commercial fuels. Potential problems due to the presence of water in the fuel include corrosion of the fuel tank and parts of the oil handling system and gum formation in the fuel during storage and handling. It has been a practice to reduce the water content of fuels

to the lowest reasonable level to prevent corrosion and sediment or gum formation. Although water within an emulsified fuel may behave differently than water contained in conventional fuels, there is no reason to believe that these problems will not exist. In fact, some of the major problems encountered in tests with fuel-in-water emulsion fuels for aircraft have been corrosion and filter blockage.

Another problem in storing and transporting emulsified fuels might be freezing of the water droplet in cold weather. Freezing may cause breaking of the emulsion, blockage of fuel lines and filters, and excessive wear on pumps and valves during handling.

Proper maintenance of blending equipment would be required to prevent difficulties from scaling and corrosion of the metering system for water and the emulsifying agent.

The addition of water would increase the dew point of the flue gas, so that greater consideration should be given to condensation problems.

Other Considerations

If the use of emulsified fuels becomes commercially feasible, several details would need to be examined more thoroughly. These include:

(1) Is water quality critical? For example, is distilled water required to prevent corrosion and deposits in the nozzle and/or heat exchanger?

(2) Will the emulsifying agents cause corrosion and/or deposits within the fuel handling or firing system?

(3) Which of the many emulsifying agents available should be used to produce emulsions with the necessary long-term stability?

(4) Will emulsifying of fuels add significantly to total cost of operation?

Thermal Effects of Emulsions

Flame Temperature

Adding any material that is not a fuel to a combustion process will lower the theoretical flame temperature due to the expenditure of energy to heat the extra material up to the flame temperature. Therefore, adding water to a combustion process by firing a fuel oil-water emulsion suppresses peak flame temperatures. Because the mass of water added to the fuel is small compared to the mass of the air required to burn the fuel, the effect of the water in suppressing flame temperatures is less than might be anticipated.

Figure 8 shows calculated theoretical flame temperatures for combustion, in an adiabatic system, of fuel oil and fuel oil-water emulsions containing up to 50 percent water. The range of the fuel-air ratio in Figure 8 is zero to 100 percent excess air. Actual peak flame temperatures in a real combustion device would be lower due to heat transfer from the gas to the walls of the device during the combustion process.

Adding 50 percent water to the fuel reduces theoretical flame temperatures by 260 F at zero excess air, 245 F at 25 percent excess air, 190 F at 50 percent excess air, 150 F at 75 percent excess air, and 120 F at 100 percent excess air. It can be seen from Figure 8 that increasing excess air by about 15 percent reduces flame temperatures more than adding sufficient water to the fuel to produce an emulsion containing 50 percent water.

NO_x Formation

One potential benefit of any reduction in flame temperature is a reduction in NO_x emissions. There is evidence that NO_x formation within combustion systems is more closely related to peak flame temperatures than any other single variable.

Figure 9 shows the theoretically predicted nitrogen oxides concentration at the peak flame temperature for combustion of fuel oil and fuel oil-water emulsions. The model used for these calculations assumes chemical equilibrium concentrations of all species included in the analysis at the peak flame temperature. Reaction kinetics, or the time required to achieve equilibrium conditions are ignored and, therefore, these results can only serve as a guideline as to the general effect of water in the fuel on nitrogen oxide emissions. Actual nitrogen oxide emissions would be significantly below these calculated values.

Flue Gas Loss

Assuming that the flue-gas temperature remains constant, the addition of inert material, such as water, to fuel will tend to lower the thermal efficiency of a combustion system. This occurs as a result of the energy carried out in the flue gas by the additional inert material. Moreover, the water will reduce the heating value of the fuel by the amount of energy necessary to vaporize the water.

Although the addition of large quantities of water to the fuel (up to 50 percent water) would be expected to significantly increase flue-gas loss, the effect is not marked. This occurs because, even at stoichiometric conditions, at least 14 times as much mass enters the combustion system as air than as fuel. Adding 50 percent water to the fuel only increases the total mass by 1 part in 30 or about 3 percent.

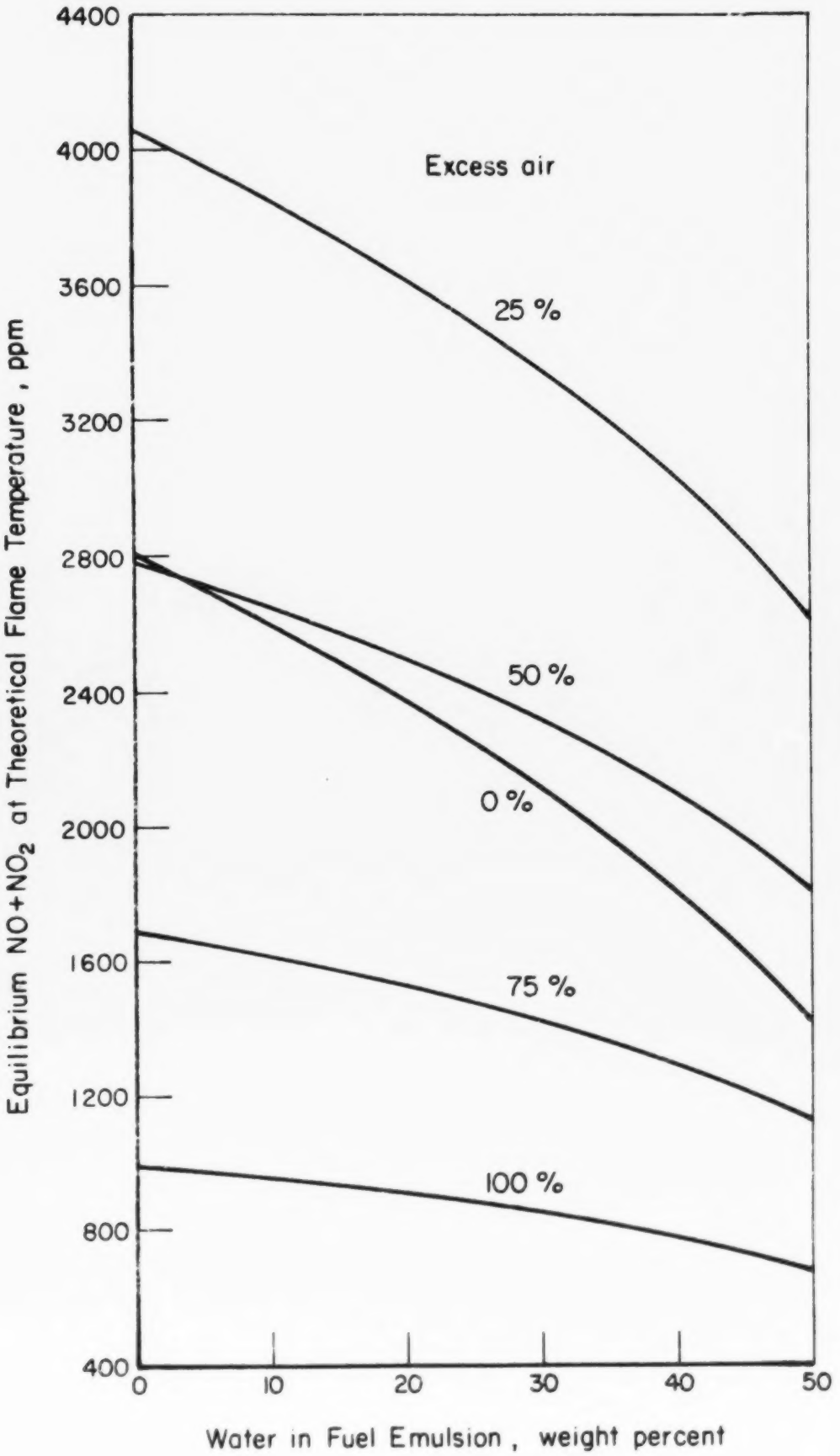

FIGURE 9. EQUILIBRIUM NITROGEN OXIDES CONCENTRATION IN FUEL OIL AND FUEL OIL-WATER EMULSION FLAMES AT THEORETICAL FLAME TEMPERATURES

Figure 10 shows calculated flue-gas loss as a percent of heating value for fuel oil and fuel oil-water emulsions containing up to 50 percent water at flue gas temperatures of 200 F, 500 F, and 800 F. It can be seen that adding 50 percent water to the fuel increases the flue-gas loss by less than 4 percent at flue-gas temperatures of 800 F, by about 2 percent at 500 F, and by less than 1 percent at 200 F.

Since the sacrifice in overall efficiency is relatively minor it appears that, if firing fuel oil-water emulsions will significantly reduce air pollutant emissions, the loss in efficiency would not be a deterrent to the use of this technique.

ACKNOWLEDGMENTS

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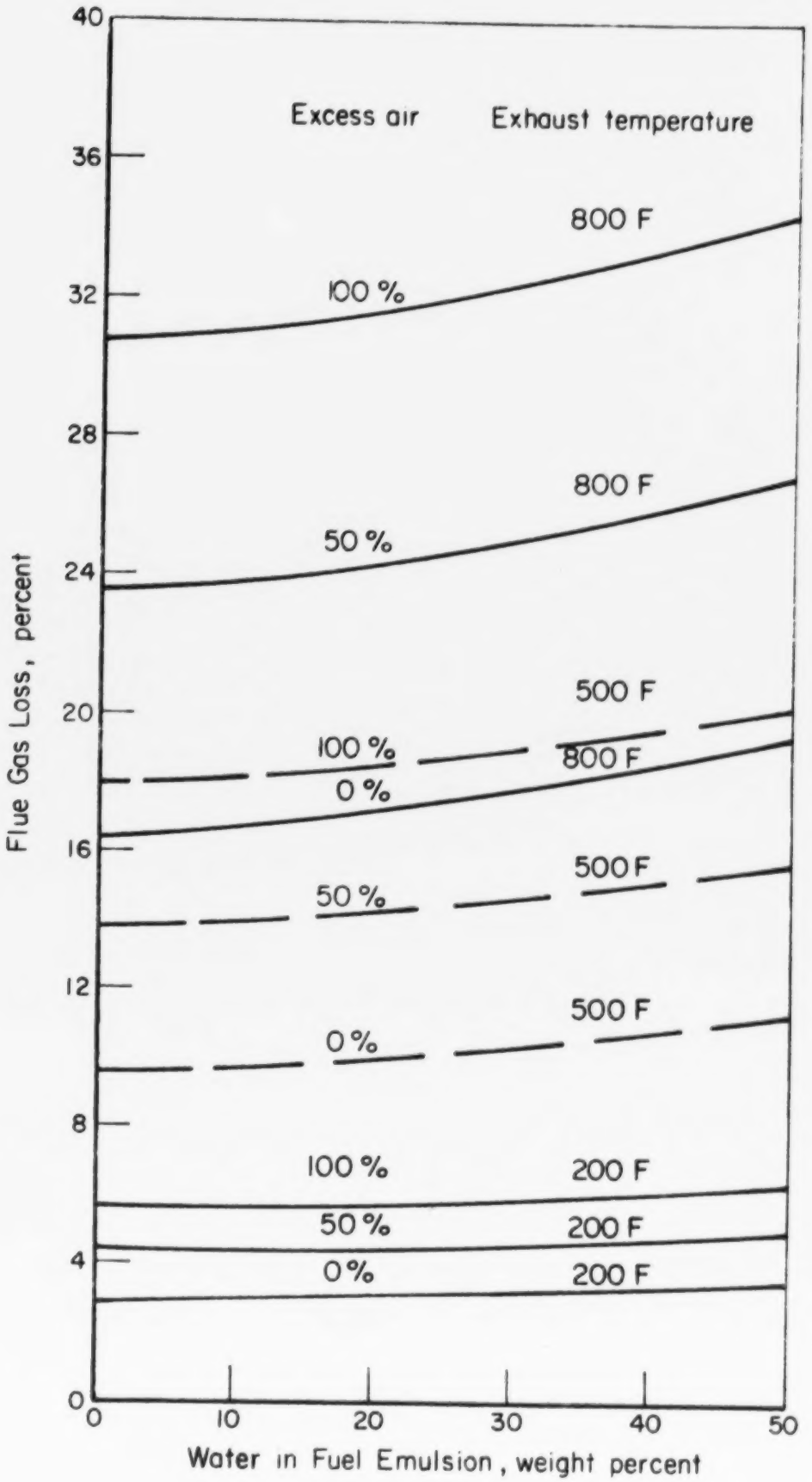

FIGURE 10. FLUE GAS LOSSES FOR COMBUSTION OF FUEL OIL AND FUEL OIL-WATER EMULSIONS AT 0, 50, AND 100 PERCENT EXCESS AIR

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